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THE TEMPERATURE OF THE SUN. I.

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[Translated from the German in *Himmel und Erde*, by FREDERICK H. SEARES.]

The problem of determining the temperature of the Sun appears at first glance to be quite insolvable. It is well known that difficulties, scarcely to be overcome, oppose the attempts to determine accurate values for the high temperatures occurring in laboratory work and in technology; while for the highest temperatures which can be produced on the Earth, the problem has in no way been solved with satisfactory accuracy. How much greater, therefore, must be the difficulties when we attempt to determine the temperature of a body separated from us by nearly 100,000,000 miles, and which in consequence cannot be handled and manipulated as the burning or glowing object in the laboratory. In truth, the difficulties confronting the investigator are great, and so far they have in part proved insurmountable.

But when have the mere difficulties of a problem prevented men from attempting a solution? On the contrary, they have proved an allurement; for the satisfaction incident upon the successful solution of a problem increases with the expenditure of energy necessary to obtain the result; and with the great multitude the profit to be expected in fame and honor, and eventually in power and wealth, is a sufficient inducement.

In the extraordinarily numerous attempts to determine the solar temperature this last incitement has not been present; for the result can have only a purely scientific, or at the most, a general

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The temperature scale used in this article is the Centigrade.—*Translator.*

interest for mankind — never such an interest as is aroused by the opening of new lines in technology, or by the introduction of new industrial methods.

In the earliest times it was recognized that man owed his very existence to the Sun, the dispenser of light and heat. This dependence has been acknowledged in various ways: by the universal division of time into days and years according to the motion of the Sun, a custom dating from the remotest antiquity; by his introduction as the source of life into the mythologies of many peoples; and even at the present day by his presence as the central idea in the religion of the Sun Worshipers.

In astronomical science the Sun was considered for centuries as a burning heavenly body, burning as a piece of wood burns in our own atmosphere; but at the beginning of the present century this idea fell into disrepute through the influence of HERSCHEL, who assumed the Sun itself to be a dark body surrounded by an intensely luminous and radiant atmospheric shell. In apparent agreement with this theory was the evidence afforded by sunspots, whose dark centers were thought to be layers of clouds seen through openings in the photosphere protecting the solar surface from the intense radiation of the atmosphere above. With a means of protection from heat thus provided, it was characteristic of the thought of the time to fancy the Sun inhabitable. The living being able to recognize the all-ruling God, and therefore in a position to attain the highest goal of nature, was, according to that thought, the crown of creation, and an uninhabitable world was therefore without reason. To-day such speculations are without influence for the majority of investigators. We admire no longer the harmonious ordering of the universe without recognizing the existing arrangement as only one of an infinitely great number of possible arrangements — *the* one which best conforms to the conditions of nature, or which can best adjust itself to them.

Another idea in harmony with HERSCHEL'S theory was that the shining envelope of the Sun did not possess an especially high temperature, that it merely shone, and that heat was generated only when the rays fell upon some body.

In the middle of the century two great revolutionary discoveries were made which dispatched with a single blow all such ideas.

They were the law of conservation of energy with the related mechanical theory of heat, and the principles of spectrum analysis.

It would lead too far to explain these in detail here, and merely the final results in their relation to the solar constitution as accepted by the majority of scientists will be given, with the risk that such a procedure will be unsatisfactory to many.

We are to imagine the Sun as an enormous glowing ball of gas, whose temperature diminishes from the center outward. At a certain depth, and in consequence of causes analogous to those acting in our own atmosphere, a part of one or more of the glowing gases is condensed into cloudlike forms. The layer containing these is called the photosphere; it is the region from which the bulk of the heat and light are emitted, and forms at the same time the visible sharp outline of the Sun. With this idea of the solar constitution it appears that properly one cannot speak of a temperature of the Sun, since for different parts the temperature is quite different; and if from the solar radiation we determine a temperature, it must refer to the point of emission, namely, the photosphere. Our problem is therefore limited to the determination of the temperature of the photosphere. Here we meet difficulties at once; for in the study of radiation the constitution of the radiating body is by no means immaterial. This has been shown in a previous article in this periodical (*Himmel und Erde*, Bd. IX, Heft 6) in connection with the subject of emission, and may be assumed for the present purpose. There need be remembered only the instance where particles of glass and metal were subjected to the same temperature. Although the two substances were of the same temperature, the glass radiated but little heat and light as compared with the metal, or as it may be stated, the luminous power of the glass was far less than that of the metal. Since the emissive power of the particles of the photosphere is unknown, it is necessary to make an assumption as to its value, if we are to determine the temperature of the photosphere from the intensity of its radiation. The simplest assumption for this value is unity — *i. e.* equal to the emissive power of an absolutely black body. It is commonly known that upon this assumption we obtain the minimum value for the solar temperature. If the emissive power is less than 1, the temperature is higher. In what follows it is to be understood that the term solar temperature refers to that temperature which the photosphere would have in case its emissive power were unity. This does not remove all of the difficulties, however.

According to our assumptions the photosphere consists not of a solid body, but of a layer of gas in which solid particles are suspended. This layer itself can scarcely possess a uniform temperature; the inner portions must be much hotter than the outer. Further, the inner portions emit radiation, which in its passage through the outer layers is only partially absorbed, and therefore we cannot speak of a definite temperature as belonging to the photosphere, but only of an average temperature which may be defined as the sum of the radiation effects from all parts of the photospheric layer. But with such a constitution there enters a variation in the emissive power. That quantity for the whole photosphere depends upon two factors, namely, the number of solid particles per unit area in the photosphere, and the absorbing power of the overlying layers of gas. If the emissive power of the particles themselves be unity, that of the photosphere, as a whole, will always be less than unity. The greater the number of particles, the greater will be the emissive power; but by increasing the number of particles the emissive power can be made 1 only when the absorptive power of the outer layers is infinitesimal.

It is not easy to see to what extent these factors are operative; it results, however, that the assumption, emissive power = 1, is not accurate, but that the value is too large.

From the observation of solar radiation, therefore, we can solve only the following: *To determine the temperature of an absolutely black body having the same apparent diameter as the Sun, and the same radiation effects.*

We are now in a position to understand what will be meant in future by temperature of the Sun. There are already considerable difficulties to be encountered in the solution of the problem, and they will increase quite extraordinarily as the solution progresses.

It must now be asssumed that we are able with appropriate apparatus to determine with accuracy the intensity of solar radiation. In fact, this determination must be made at the bottom of our atmosphere, in which the rays have lost a portion of their energy by absorption. That this loss is not inconsiderable is a matter of common experience. The rising and setting Sun, for example, exercise but slight heating effect on account of the great absorption taking place in the long path through the atmosphere which the rays must traverse.

We must then determine the exact diminution in the energy of radiation corresponding to a given altitude of the Sun. With the theoretical part of this determination we cannot here concern ourselves; it is closely related to the theory of refraction in our atmosphere, and its comprehension presupposes a knowledge of mathematics not to be expected of the general reader. Such an understanding is unnecessary, for in practice we can do without the theory of extinction. We need only apparatus for measuring the intensity of solar radiation for all altitudes of the Sun from horizon to zenith. The values thus obtained for the loss by absorption can be plotted as ordinates on co-ordinate paper, with the corresponding altitudes as abscissæ, and a curve can be drawn through the plotted points. If for a later observation the loss by absorption for a certain altitude is desired, it can be read from the curve. A graphical method of this sort leads to the same results as those obtained by theory combined with observations, but even this simple procedure becomes exceedingly complicated on account of the variable absorptive power of air. At the outset the absorptive power varies with the barometric height, but since absorption depends upon the number of particles encountered by the ray, it is possible to consider the absorptive power proportional to the barometric height, which leads to a simple reduction. In a similar manner the altitude of the observer above sea-level can be taken into account. But far more uncertain is the dependence of absorption upon water vapor, the amount of which in the atmosphere is subject to sudden and extreme variations. It cannot be taken into account with accuracy since its value can be determined only for points near the surface of the earth, and not for the upper layers through which the solar rays must also pass. Again, the effect of the light cloudlike formations of the upper atmosphere, recognized by their whitish appearance on the blue sky, is uncertain, and cannot be allowed for numerically. Thus the actual absorption for each day, oftentimes for each hour, is different, and inasmuch as only mean values can be found, important errors enter into individual determinations whose effect can be eliminated, in a measure, only by the use of a great number of observations.

At the present day it is possible to determine the effect of absorption accurately to within, perhaps, ten per cent. of its true value, so that the corrected radiation values corresponding to the true solar radiation without an atmosphere are accurate, so far as they are affected by this one uncertainty, to a proportional amount.

We have proceeded so far as to get values for the solar radiation unaffected by our atmosphere, and we now come to a description of one of the most important points of the whole problem, the measurement of the radiation. At first sight this does not appear difficult; *e. g.* a thermometer which has been in the shade can be read and then exposed to the solar radiation; the column of mercury immediately rises and comes to rest 12° to 14° higher up. Radiation has increased the reading by this amount, and from this data we can determine a value for the amount of radiation, but the value would be only approximate at best; it may be in error one hundred per cent., or more.

It is an inviolable physical law that every body radiates heat in all directions, the amount of which depends only on the temperature of the radiating body, and not upon the temperature of those surrounding it. The higher the temperature, the greater is the amount of radiation. The same law holds equally for the surrounding bodies, and it thereby follows that a body of a temperature higher than its neighbors must lose heat, while those of a lower temperature must gain. The tendency is to set up a uniformity of temperature throughout all the bodies in question. It may be remarked incidentally that this is the condition toward which the whole universe tends — to an equality of temperature for all bodies and parts of bodies, be they large or small. The outlook for the future is a dismal one; for ultimately every source of energy, whether it lie in animate or in inanimate material, must become exhausted. We may console ourselves with the thought that an infinitely long time will be required for this condition of things to come about.

If now we subject a thermometer to solar radiation, and find, after a time, that the column of mercury comes to rest in a higher position than in shadow, it can be said that from this moment on, the radiation of the thermometer is equal to the energy received from the surrounding objects, not merely from the Sun, but also from the ground, from the clouds, from buildings, etc. The slightest variation in the position of the instrument changes its distance from some of the radiating bodies, and consequently the indicated temperature. Even the radiation from the screen used to protect the thermometer in determining the difference between shade and sunlight modifies the result.

The observations must be made in open air; for the introduction of glass into the path of the rays would seriously affect the result. But here air-currents, even the lightest puff, prove disturbing sources of error, since, in general, they are of a different temperature from the thermometer, and either give up or take away heat.

Besides these external sources of error, there is a whole series of internal ones, depending upon, and varying with, the construction of the apparatus used. It is, therefore, not surprising that the accurate measurement of radiation of the Sun is far from a satisfactory solution — satisfactory to the scientist who desires to obtain in his investigations the highest possible degree of accuracy. If in the measurement of solar radiation we are satisfied to accept an accuracy of twenty per cent., as will be done in what follows, in order to gain some insight into the matter, the problem may be considered as solved. Instruments designed for the measurement of solar radiation are collected together under the name of actinometers, of which certain forms are called pyrheliometers. These instruments are best classified according to whether they are arranged to give absolute or relative measurements of the energy of radiation.

With the latter sort is to be included the simple thermometer, alternately exposed to light and shadow, and also thermo-electric apparatus, the bolometer, etc., whose purpose is understood without further explanation, since they give only differences of temperature. Instruments of the first sort, for our purpose, are of greater importance. They indicate not how much the temperature of a body is increased by solar radiation, but how much heat is conducted to the apparatus by the radiation; they serve to measure the energy of the solar radiation. The temperature degree is a measure of the intensity of the heat; while for the energy a much more complicated unit must be introduced, namely, the calorie, by which we mean the amount of heat which must be applied to one gram of water at 0°, in order to raise its temperature to 1°. Ten calories, therefore, can be used in an infinite number of ways; *e. g.* 1 gram of water can be raised to 10°, or 10 grams of water to 1°, or 5 grams of water to 2°, etc. Water is chosen as a standard, each substance requiring a relatively different amount of heat to produce a given temperature effect. Much less heat is required to raise a gram of iron 1° than a gram of water, and the number expressing the ratio of the amounts of heat required to produce the same increase in temperature in the same amounts of water and a given substance is called the specific heat of the substance. For example, the specific heat of iron is 0.11, which means that, to raise 1 gram of iron 1°, 0.11 calories is required.

The determination of the number of calories alone is not sufficient for the determination of the heat conducted by radiation; for the amount received increases with the time during which the radiation acts, and with the increase of the surface exposed to the rays.

The energy of radiation is therefore expressed in calories, referred to 1 square centimeter of surface and to a duration of radiation of one minute. Every actinometer must have as an essential part a surface which is exposed to the radiation, and whose area and specific heat are accurately known. It is very important that the surface should absorb as much as possible of the radiation, which means that it must be rough and black; a polished silver mirror, for example, is scarcely affected by the solar rays.

The first to concern himself with this problem was POUILLET, who made his experiments in 1838. The pyrheliometer used by him was of the following construction:—

One end of a flat cylindrical vessel of sheet-silver was blackened with soot, and placed so that the solar rays fell perpendicularly upon it. The vessel was filled with about 100 grams of water, whose increase in temperature was measured by a thermometer projecting into the vessel. During the observation the vessel was rotated about its axis, in order that the contents might become of the same temperature throughout. Many later observers have retained POUILLET'S method in its essentials, and have introduced only slight modifications; for example, CROVA used mercury instead of water.

Of an entirely different construction was the actinometer of VIOLLE. The surface exposed to radiation was small, and was protected from wind and the radiation of surrounding objects by a complete covering of constant temperature. The blackened bulb of a thermometer served as the surface, and it was placed in the center of a large double-walled sphere, which was kept at a constant temperature by flowing water. The exposure of the thermometer bulb to radiation was made possible by a tube passing from the center outward, which contained a diaphragm of the same diameter as the thermometer bulb. When the tube was directed toward the Sun, the bulb lay in the path of the rays.

As a third fundamental type of actinometer, we may consider that of ÅNGSTRÖM. It consisted essentially of two equal copper discs, blackened upon one side and exposed to the Sun. In the centers of the unexposed surfaces of these discs were attached thermo-elements, which connected with a galvanometer gave accurately the temperature of the discs. The two discs were alternately exposed to the radiation and their differences of temperature measured. An especial advantage of this apparatus (constructed in 1887) over the others is its symmetrical arrangement, by means of which several external sources of error are excluded.

It may be further stated, that with none of these apparatus is it necessary to allow the radiation to act until no further increase of temperature is perceptible. With short intervals of alternation between light and shade, it is possible to deduce the desired quantities from appropriate formulæ.

There is yet a whole series of actinometers which have been used, but they can all be referred to one of the three types above, and do not need further explanation. On the contrary, of especial interest are the *numbers* which have been obtained for the energy of radiation of the Sun by means of these various instruments. Arranged chronologically, they show a decided increase, corresponding to the development of apparatus and methods of observation.

OBSERVER.	YEAR.	CALORIES.
POUILLET	1838	1.76
FORBES	1842	1.82
HAGEN	1860	1.9
VIOLLE	1875	2.54
CROVA	1878	2.3
LANGLEY	1884	3.07
SAVELIEF	1880–1890	3.47
PERNTER	1880–1890	3.28
ÅNGSTRÖM	1894	4.0

From this series of values, there appears to be no question but that the true value of the energy of solar radiation, or the so-called solar constant, lies between 3.5 and 4.0 calories, and that we may take, as the most probable value, 3.75, which it will be noticed, is about double the first determinations.

At the end of this article, several interesting computations will be carried through with the aid of this constant, but we will now proceed with the main problem.

With a variation of only fifty per cent. in the determinations of solar radiation, a similar variation in the deduced values of the solar temperature might be expected. This is not the case, however; the determinations of this temperature differ from each other so enormously, that in consequence the results have long since been viewed with a certain contempt. For example, it may be noted that POUILLET deduced the round number 1,500° for the solar temperature, while SECCHI, early in 1870, with a similar apparatus, found the value 10,000,000°.

Wherein, then, do these inconceivable differences enter? The answer to this question leads us at once to the most difficult, and at the same time the most interesting, part of our problem. It is required to determine from relatively small differences of temperature the value of an extremely high temperature, and naturally any error in the temperature difference appears enormously multiplied in the result. Let us begin, for example, with an error of 1° in a temperature difference of 10°; if the true result should be 10,000°, it will appear, in consequence of the error, increased by 1,000°. This, however, in itself is insufficient to explain the great discrepancies which occur; a much more uncertain source of error arises from a lack of knowledge concerning the law of radiation — the law connecting the temperature of the radiating body with the energy of the radiation emitted. A law of this sort can be deduced from observations in the laboratory. A sheet of platinum, for example, can be heated to a temperature of 1,000°, and then its radiation can be studied. But aside from the great practical difficulties which oppose such investigations, there is the unfortunate circumstance that the temperature of the Sun is doubtless far higher than any temperature which can be produced for measurement in the laboratory; from the relation between radiation and temperature from 0° to 1,000° must be inferred the relation for temperatures from 1,000° to 10,000°.

If the relation between temperature and radiation be plotted as a curve, with temperatures as abscissæ, that part of the curve between 0° and 1,000° can be accurately determined by observation. The course of the nine-tenths of the curve beyond 1,000° can be judged only from the course of the first tenth, and it is evident that beginning with 1,000°, it may take courses whose ordinates for higher temperatures vary enormously. Such an uncertainty it was which affected SECCHI's determination; and most significant is the result when SECCHI'S observations are reduced by the same law as used by POUILLET. A temperature of 1,400° is thus obtained from the same numbers, which with the application of another law by SECCHI gave 10,000,000°.

The famous NEWTON was the first to investigate the relation between radiation and the temperature of the radiating body. He came to the conclusion that the rate of cooling of a radiating body is directly proportional to the difference in temperature between the radiating body and the bodies surrounding it. It is assumed here that the radiating body is of a uniform temperature throughout, and that its power of emitting heat is infinitely great. These ideal conditions are the more nearly satisfied the slower is the cooling of the surface, *i. e.* the smaller is the temperature difference. They are not satisfied in the case of the Sun, although it cannot be denied that with a body gaseous at the surface, like the Sun, the convection currents of the gas may afford a certain approximation to the ideal conditions.

It has been shown that NEWTON'S law of cooling can be considered only as a rough approximation, applicable for small temperature differences, but quite misleading when these differences are large. In recent times the most various attempts have been made to determine a law which should be valid for the highest temperatures. The most important of these will now be noticed.

First are the French physicists DULONG and PETIT, who continued NEWTON'S investigations. They found as a satisfactory law for the temperature interval of 280° used by them, that the amount of heat radiated by a body diminished according to a geometrical progression with a uniform diminution of temperature. No theoretical considerations can be advanced in favor of the applicability of this purely empirical law to higher temperatures; and to-day there is no doubt that values of the solar temperature extrapolated by means of this law are too small, but not in the degree in which values obtained by NEWTON'S law are too large. It may be remarked that POUILLET computed according to the law of DULONG and PETIT, while SECCHI used NEWTON'S law.

A second law applicable to temperatures between 0° and 300° was deduced by ROSETTI; its form involves a mathematical expression not easily expressed in words.

Only during the last decades have considerable advances been made in the determination of the form of this law. First among them is the somewhat complicated mathematical form found by WEBER, a Swiss, which represents satisfactorily all the experimentally deduced relations up to 1,000°, but which is not susceptible of a theoretical interpretation. The Austrian physicist STEFAN has determined an extremely simple law, which, with a slight modification, retains its validity to 1,300°, as shown by recent tests by the Berlin physicists LUMMER and PRINGSHEIM. STEFAN'S law states simply: The amount of heat radiated by a body is proportional to the fourth power of its absolute temperature—to the 3.96 power according to LUMMER and PRINGSHEIM. Besides the extreme simplicity of this law, there is the circumstance that BOLTZMANN has been able to establish it theoretically, from the electro-magnetic theory of light and the mechanical theory of heat.

It is of especial importance to note that the two last-named laws of WEBER and STEFAN differ so slightly for the highest temperatures yet investigated, that it is extremely probable the values obtained by extrapolation in their application to the Sun will be near the true values.

It is possible to conclude from the agreement of the laboratory experiments that the resulting solar temperatures will not vary by more than half the true value, which, in view of the difficulties of the problem, is really a satisfactory solution. With the application of one of these laws, it is therefore possible to bring order into the chaos of solar temperatures, as is shown by the following list, computed according to STEFAN'S law:—

OBSERVER.	SOLAR TEMPERATURE.
POUILLET	5,600°
SECCHI	5,400
VIOLLE	6,200
SORET	5,500
LANGLEY	6,000
WILSON and GRAY	6,200
PASCHEN	5,000
ROSETTI	10,000 { according to his own law.

There is here doubtless justification for the assumption that the solar temperature is greater than 5,000° and less than 10,000°; the value $T = 6,250^\circ$ corresponds to the mean of the above determinations.

The reader will perhaps breathe again in the hope that he is now to be released from the difficulties of the discussion of the solar temperature; but this hope is unfortunately not to be satisfied, for the value T thus obtained represents in no way the temperature of the photosphere as it was in the beginning defined, but only that temperature which the photosphere would have on the assumption that the radiation has come unimpeded to the Earth. But the Sun possesses an atmosphere which, similarly to that of the Earth, absorbs a portion of the radiation; the actual temperature is therefore higher than the value we have obtained. That such an atmosphere exists is shown by the direct view of the Sun through a telescope. Thus seen, the disc is not uniformly bright, as it must be in the case of a simple glowing sphere, but at the edges is much darker, owing to the longer path through the Sun's atmosphere which must be traversed by the rays here than at the center. It is possible to compute the relative lengths of the latter through the atmosphere for different points of the disc, which, combined with the directly observed increase in absorption toward the limb, leads to the law of absorption, and thus it is possible to compute the total absorption of heat rays due to the Sun's atmosphere. Observations have shown that, as in the case of the Earth's atmosphere, different kinds of rays are very differently absorbed — the nearer they lie to the violet end of the spectrum, the greater is the absorption. The rays lying at the other end of the spectrum are least absorbed, though even here very considerably, since the most careful observations by H. C. VOGEL, and the recent determination of FROST show that the transmission coefficient lies between 0.72 and 0.79. It is therefore necessary to multiply the determined radiation by 1.5 in order to get the true value, which increases the solar constant to 5.6 calories. How the solar temperature is now to be computed is as yet undetermined, for STEFAN'S law is no longer applicable; we may *assume* that T lies between 7,000° and 10,000°.

For a comparison with terrestrial temperatures, it may be remarked that the temperature of the electric arc varies from 3,000° to 3,500°; the temperature of a very long electric spark is much higher, running up to 20,000°, and even higher.

(To be concluded in No. 65.)